

Searches for neutrinoless double beta decay

Bernhard Schwingenheuer

Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

E-mail: b.schwingenheuer@mpi-hd.mpg.de

Abstract. Neutrinoless double beta decay is a lepton number violating process whose observation would also establish that neutrinos are their own anti-particles. There are many experimental efforts with a variety of techniques. Some (EXO, Kamland-Zen, GERDA phase I and CANDLES) started take data in 2011 and EXO has reported the first measurement of the half life for the double beta decay with two neutrinos of ^{136}Xe . The sensitivities of the different proposals are reviewed.

1. Introduction

For many isotopes like ^{76}Ge β decay is energetically forbidden, but double beta decay ($2\nu\beta\beta$) is allowed

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e \quad (1)$$

This was suggested very early [1] and - following the idea of Majorana that neutrinos could be their own anti-particle [2] - also the possibility of neutrinoless double beta decay $0\nu\beta\beta$ was anticipated shortly afterwards [3] (for a review see [4, 5]). The latter case is very interesting since lepton number is violated and it would establish that the neutrino is its own anti-particle. The experimental signature in this case is a line at the $Q_{\beta\beta}$ value of the decay if the sum of the electron energies is plotted.

Searches for double beta decay date back to the beginning of nuclear physics and nowadays more than a dozen large scale experimental programs are suggested. These programs are compared in this article and also the status of theoretical matrix element calculations is discussed. For general reviews the reader is referred to the literature, e.g. [6, 7, 8].

There are also other related processes like double positron decay or double electron capture processes. While $0\nu\beta\beta$ is already a suppressed process, the other decays are expected to be even rarer unless there is some resonance enhancement [9, 10, 11, 12]. In this article only $0\nu\beta\beta$ decay searches are discussed.

2. Motivation

The observation of neutrino oscillation establishes that these particles have mass [13]. Since neutrinos have no electric charge, there is no known symmetry which forbids additional terms in the effective Lagrangian beside the standard Dirac mass term m_D [7]:

$$-L_{\text{Yuk}} = m_D \bar{\nu}_L \nu_R + \frac{1}{2} m_L \bar{\nu}_L (\nu_L)^c + \frac{1}{2} m_R \overline{(\nu_R)^c} \nu_R + h.c. \quad (2)$$

$$= \frac{1}{2} (\bar{\nu}_L, \overline{(\nu_R)^c}) \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ \nu_R \end{pmatrix} + h.c. \quad (3)$$

29 The subscript L stands for the left-handed chiral field $\nu_L = \frac{1}{2}(1 - \gamma_5) \nu$ and R for the right-
 30 handed projection $\frac{1}{2}(1 + \gamma_5) \nu$. The superscript C denotes charge conjugation. The m_R term
 31 describes therefore an incoming neutrino and an outgoing anti-neutrino, i.e. lepton number is
 32 violated by 2 units. The eigen states of the mass matrix are of the form $(\nu + \nu^c)$. Consequently
 33 neutrinos are expected to be - in general - their own anti-particles, i.e. Majorana particles.

What is the best experimental approach to establish that our known neutrinos are Majorana particles? Neutrinos (or anti-neutrinos) are produced in charged weak current reactions and - depending on the charge of the associated lepton - only one chiral projection couples. For example in β decay $n \rightarrow p e^- \bar{\nu}_{e,R}$, a right-handed anti-neutrino couples:

$$\bar{\nu}_{e,R} = \bar{\nu}_e \frac{1}{2}(1 + \gamma_5) = \sum_{i=1}^3 U_{ei}(\bar{\nu}_{i,h=+1} + \frac{m_i}{E} \bar{\nu}_{i,h=-1}) \quad (4)$$

34 Here, U is the PMNS mixing matrix, ν_i are the mass eigen states with mass eigen values m_i , E
 35 is the neutrino energy and h stands for the helicity of the anti-neutrino.

For a Dirac particle these anti-neutrinos can only undergo detection reactions like $p \bar{\nu}_{e,R} \rightarrow n e^+$. If, on the other hand, neutrinos are Majorana particles, then the $\nu_{i,h=-1}$ component can undergo the reaction $\nu_{e,L} n \rightarrow p e^-$ with

$$\nu_{e,L} = \frac{1}{2}(1 - \gamma_5)\nu_e = \sum_{i=1}^3 U_{ei}(\nu_{i,h=-1} + \frac{m_i}{E} \nu_{i,h=+1}) \quad (5)$$

36 The rate of this reaction¹ is however suppressed by the factor $(m_i/E)^2$ which is e.g. 10^{-14} for a
 37 neutrino mass of 0.1 eV and a neutrino energy of 1 MeV. Thus solar neutrino experiments for
 38 example will not be able to establish the nature of neutrinos.

39 The alternative is the search for $0\nu\beta\beta$ where the neutrino only enters as a propagator
 40 $\simeq m_{\beta\beta}/q^2 = \sum_i U_{ei}^2 \cdot m_i/q^2$. The coupling strength $m_{\beta\beta}$ is called the effective Majorana mass.
 41 Since one mole contains a large number of nuclei, the factor $(m_i/E)^2$ is compensated. For 35
 42 isotopes double beta decay is the only possible decay mode. The Standard Model allowed decay
 43 with two emitted neutrinos ($2\nu\beta\beta$) has been observed for 11 isotopes with half lives between
 44 $7 \cdot 10^{18}$ y and $2 \cdot 10^{21}$ y [14, 15].

45 Part of the Heidelberg-Moscow experiment claims to have observed $0\nu\beta\beta$ of ^{76}Ge with
 46 $m_{\beta\beta} \approx 0.2 - 0.6$ eV [16]. Clearly this needs independent confirmation which poses another
 47 motivation for the experimental efforts.

48 3. Experimental sensitivity

An experiment will observe some background events λ_{bkg} which - if this number scales by the detector mass M - is given by

$$\lambda_{\text{bkg}} = M \cdot t \cdot B \cdot \Delta E \quad (6)$$

and possibly signal events

$$\lambda_{\text{sig}} = \ln 2 \cdot N_A \cdot \epsilon \cdot \eta \cdot M \cdot t / (A \cdot T_{1/2}^{0\nu}). \quad (7)$$

49 Here t is the measurement time, B the so called background index given typical in
 50 cnts/(keV·kg·y), ΔE is the width of the search window which depends on the experimental
 51 energy resolution, N_A is the Avogadro constant, ϵ the signal detection efficiency, η the mass
 52 fraction of the $0\nu\beta\beta$ isotope, A the molar mass of this isotope and $T_{1/2}^{0\nu}$ its half life.

¹ Since the charge of the outgoing lepton is the same as in the production process, U and not U^* enters here.

Table 1. List of most interesting $0\nu\beta\beta$ isotopes. Half lives are taken from [14, 15] while all other numbers are from [7].

isotope	$G^{0\nu}$ [$\frac{10^{-14}}{y}$]	$Q_{\beta\beta}$ [keV]	nat. abund. [%]	$T_{1/2}^{2\nu}$ [10^{20} y]	experiments
^{48}Ca	6.3	4273.7	0.187	0.44	CANDLES
^{76}Ge	0.63	2039.1	7.8	15	GERDA, Majorana Demonstrator
^{82}Se	2.7	2995.5	9.2	0.92	SuperNEMO, Lucifer
^{100}Mo	4.4	3035.0	9.6	0.07	MOON, AMoRe
^{116}Cd	4.6	2809	7.6	0.29	Cobra
^{130}Te	4.1	2530.3	34.5	9.1	CUORE
^{136}Xe	4.3	2461.9	8.9	21	EXO, Kamland-Zen, NEXT, XMASS
^{150}Nd	19.2	3367.3	5.6	0.08	SNO+, DCBA/MTD

If $\lambda_{\text{bkg}} < 1$ the experimental sensitivity scales with $M \cdot t$ while for $\lambda_{\text{bkg}} >> 1$ the e.g. 90% C.L. limit on the half life (assuming there is no signal) is given by

$$T_{1/2}^{0\nu}(90\%CL) > \frac{\ln 2}{1.64} \frac{N_A}{A} \epsilon \cdot \eta \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}. \quad (8)$$

If systematic errors become important e.g. if the energy resolution is not well known or the assumption of the background shape is not correct, then the sensitivity is reduced.

4. Theoretical considerations

The half life for $0\nu\beta\beta$ is given by [7]

$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) |M_{0\nu}|^2 \frac{m_{\beta\beta}^2}{m_e^2} \quad (9)$$

Here $G_{0\nu}$ is the calculable phase space factor (Tab. 1), m_e is the electron mass and $M_{0\nu}$ is the nuclear matrix element whose calculation is difficult and can only be done using approximations. For a review see for example [6, 8].

While the observation of $0\nu\beta\beta$ would manifest lepton number violation and the neutrino's Majorana nature, the underlying physics can only be disclosed if the observed $T_{1/2}^{0\nu}$ for different isotopes and possibly other variables like the angle between the emitted electrons is compared to theory. Consequently, there is a large interest in nuclear matrix element calculations and substantial progress has been made during the last years. Traditionally, nuclear shell model (NSM) and quasi particle random phase approximation (QRPA) calculations have been performed. Recently new approaches like the interacting boson model (IBM), the generating coordinate model (GCM) and the projected Hartree-Fock-Bogoliubov (pHFB) method have been applied. A discussion of these calculations is given in [27].

The results of these calculations are shown in Fig. 1. The following statements can be made concerning the status:

- There is no large variation for the NME between the different isotopes. This might be due to the fact that only neighboring neutrons in a nucleus contribute to the decay [17, 20].
- For the NSM, all values are systematically lower than for other methods. Possible reasons for this effect are discussed in the literature [17, 28].
- The differences between the QRPA calculations of different groups are now quite small.

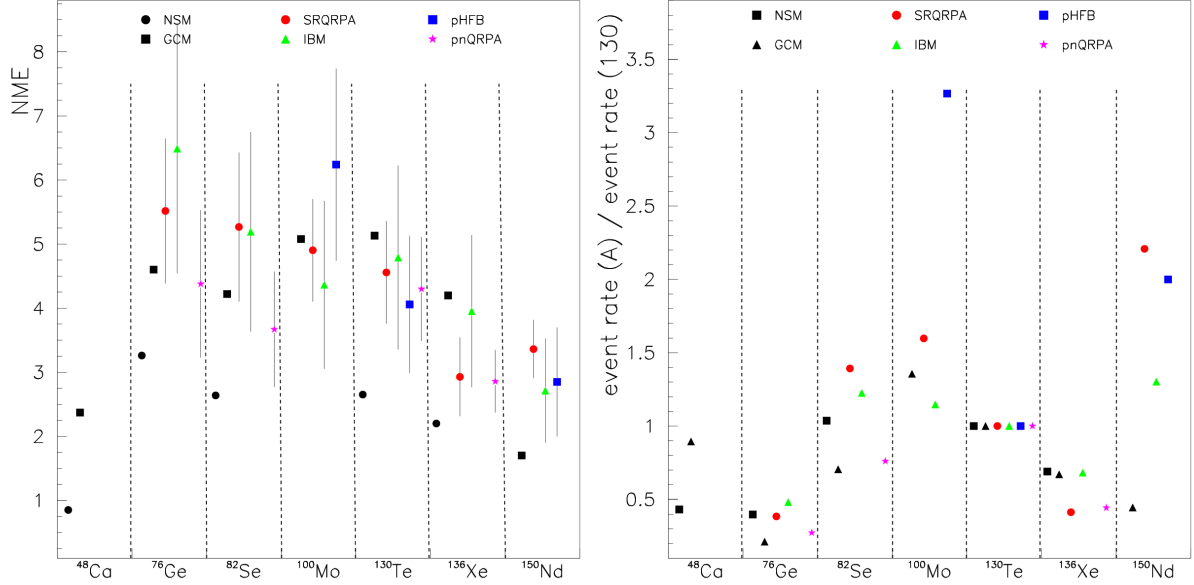


Figure 1. Left: Different calculations for nuclear matrix elements for $0\nu\beta\beta$ decay for light neutrino exchange. NSM = Nuclear shell model [17, 18], SRQRPA = self-consistent renormalized quasi-particle random phase approximation [19, 20, 21] (matrix elements are scaled by 1.14 to compensate for different phase space factors), pnQRPA = proton-neutron quasi particle random phase approximation [22], GCM = generating coordinate method [23], IBM = interacting boson model [24, 25] (matrix elements are scaled by 1.18 to estimate the effect if the UCOM short range correlation instead of the Jastrow type would have been used [8]), pHFB= projected Hartree-Fock-Bogoliubov model [26]. Right: ratio of expected $0\nu\beta\beta$ events per kg target mass for the different models normalized to ^{130}Te .

- For a given isotope the calculations spread by typically a factor of 2, i.e. a factor of 4 for $T_{1/2}^{0\nu}$.
- The role of short range correlations has been studied and the UCOM correction has emerged as standard [29]. Alternatively, a self consistent implementation was first applied to SRQRPA [20] and later to other methods [18, 26] and resulted in small changes.
- Experimental input can have a large shift of the result. For example charge exchange reaction measurements of $^{150}\text{Nd}(^3\text{He}, t)$ and $^{150}\text{Sm}(t, ^3\text{He})$ [30] result in a quenching factor of 0.75 for the g_A coupling and hence a reduction of the matrix element by 25% for ^{150}Nd [21]. In this calculation, deformation was treated for the first time in a QRPA calculation. For ^{76}Ge and ^{76}Se , the proton and neutron valence orbital occupancies have been measured [31, 32]. If the models are adjusted to reproduce these values, the NSM result increases by 15% [18] while the QRPA results are reduced by about 20% [33, 34]. Hence the difference between NSM and QRPA becomes half as large.

The calculations are performed for the standard light neutrino exchange but results for other mechanisms like SUSY particle exchange are also available [35, 19].

In order to see whether some isotopes are better suited for $0\nu\beta\beta$ decay searches from a theoretical point of view, the number of expected decays per isotope mass can be compared. This value includes the phase space factor, the matrix element and the mass number A . For the comparison it is sufficient to look at the ratio of decay rates and in this case, some of the systematic effects of the matrix element calculations cancel since there are typically correlations

Table 2. Selection of $0\nu\beta\beta$ experiments.

experiment	isotope	mass [kg]	method	location	time	ref.
past experiments						
Heidelberg-Ms.	^{76}Ge	11	ionization	LNGS	-2003	[16]
Cuoricino	^{130}Te	11	bolometer	LNGS	-2008	[36]
NEMO-3	$^{100}\text{Mo}, ^{82}\text{Se}$	7,1	track.+calorim.	Modane	-2011	[37]
current experiments						
EXO	^{136}Xe	175	liquid TPC	WIPP	2011-	[15]
Kamland-Zen	^{136}Xe	330	liquid scintil.	Kamioka	2011-	[38]
GERDA-I/II	^{76}Ge	17/35	ionization	LNGS	2011-/13	[39]
CANDLES	^{48}Ca	0.35	scint. crystal	Oto Cosmo	2011-	[40]
funded experiments						
NEXT	^{136}Xe	100	gas TPC	Canfrac	2014	[41]
Cuore0/Cuore	^{130}Te	10/200	bolometer	LNGS	2012/14	[42]
Majorana Demo.	^{76}Ge	30	ionization	SUSEL	2014	[43]
SNO+	^{150}Nd	44	liquid scint.	Sudbury	2014	[44]
proposal, proto-typing						
SuperNEMO	^{82}Se	7/100-200	track.+calorim.	Modane	2014/-	[45]
Cobra	^{116}Cd		solid TPC	LNGS		[46]
Lucifer	^{82}Se		bolom.+scint.	LNGS		[47]
DCBA/MTD	^{150}Nd	32	tracking			[48]
MOON	$^{82}\text{Se}, ^{100}\text{Mo}$	30-480	track.+scint.			[49]
XMASS	^{136}Xe		liquid scint.	Kamioka		[50]
AMoRE	^{100}Mo	100	bolom.+scint.	YangYang		[51]
Cd exp.	^{116}Cd		scint.			[52]

among the isotopes for a given method. The right hand plot of Fig 1 shows these ratios for the different models normalized to the decay rate of ^{130}Te . One sees that ^{76}Ge is less favorable. The expected decays per kg vary between 20% and 50% of the rate of ^{130}Te . In other words: if all experimental parameters were the same then one would need a factor of ≈ 3 more target mass in a ^{76}Ge experiment to have the same sensitivity. In reality this is not the case, i.e. the superior energy resolution of Ge detectors compensates this effect.

5. Comparison of experiments

The experiments searching for $0\nu\beta\beta$ decay use a large variety of detection mechanisms and background reduction methods, see Tab. 2. The current status of almost all of them is described in these proceedings. Therefore a more detailed discussion is omitted here. Instead the key performance numbers are taken for a comparison of the sensitivities of some experiments.

Since experiments use different isotopes a relative scaling factor for the different matrix elements and phase spaces has to be applied. This factor can be estimated using Fig. 1. The values used here are $f_A(\text{Ge}) = 0.35$, $f_A(\text{Se}) = 1.1$, $f_A(\text{Mo}) = 1.6$, $f_A(\text{Te}) = 1$, $f_A(\text{Xe}) = 0.55$ and $f_A(\text{Nd}) = 2.2$.

If the number of background events is large, equation 8 can be used to estimate the experimental sensitivity. A relative figure-of-merit can then be defined as

$$\text{FOM} = f_A \cdot \epsilon \cdot \eta \cdot \sqrt{\frac{M}{B \cdot \Delta E}} \quad (10)$$

One can call this the “ultimate” relative sensitivity of an experiment. Tab. 3 lists the

Table 3. Comparison of figure-of-merits (FOM) for the case of large number of background events (“ultimate sensitivity”). f_A is the scale factor for a given isotope taken from Fig. 1(right), and ΔE is the energy window which is taken here to be 1(2) full width half maximum for experiments with $> 0.5\%$ ($< 0.5\%$) resolution. Note that the efficiency is reduced by 0.7 if $\Delta E = 1 \cdot \text{FWHM}$. FOM is defined in the text.

experiment	mass [kg]	f_A	background [$\frac{\text{cnt}}{\text{keV} \cdot \text{kg} \cdot \text{y}}$]	ΔE [keV]	efficiency	enrichment	FOM
Hd-Moscow	11	0.35	0.12	8	0.8	0.86	0.8
Cuoricino	41	1	0.16	12	0.9	0.27	1.1
NEMO-3	6.9	1.6	0.002	240	0.18	0.9	1.0
EXO	175	0.55	0.004	260	0.33	0.81	1.9
Kamland-Zen	330	0.55	0.0002	250	0.5	0.9	20
GERDA-I	15	0.35	0.03	10	0.8	0.86	1.7
GERDA-II	30	0.35	0.001	6	0.8	0.88	17
Major.-Dem.	20	0.35	0.001	6	0.9	0.9	16
CUORE	750	1	0.01	10	0.9	0.27	21
SNO+	800	2.2	0.0002	230	0.33	0.056	5.4
NEXT	100	0.55	0.0002	25	0.25	0.9	18
SuperNEMO	100	1.1	0.0002	120	0.3	0.9	19
Lucifer	100	1.1	0.001	10	0.9	0.5	50

performance numbers and the figure-of-merit. For running (and past) experiments like EXO and GERDA-I the current achieved values are used which might improve with time while for the others the anticipated performance numbers are taken.²

Alternatively, the (relative) sensitivity vs. time can be estimated from equation 7 by

$$\hat{T}_{1/2}^{0\nu} > \frac{f_A \cdot \epsilon \cdot \eta \cdot M \cdot t}{\Psi(B \cdot \Delta E \cdot M \cdot t)} \quad (11)$$

Here $\Psi(\lambda_{\text{bkg}})$ is the “average” 90%C.L. upper limit of the number of signal events for λ_{bkg} background events calculated according to the method discussed in [29]. The result is shown in Fig 2. Here all experiments are assumed to start at time 0.

A few comments should be made concerning the interpretation of Tab. 3 and Fig. 2.

- If one takes the spread of the data points in Fig. 1 the factor f_A has a $\approx 20\%$ uncertainty.
- The $2\nu\beta\beta$ background is irreducible and can only be avoided with an energy resolution $\sigma < 1 - 2\%$ at $Q_{\beta\beta}$. This requirement depends of course strongly on $T_{1/2}^{2\nu}$ which varies by a factor of 300 for the isotopes considered. For some experiments this background is not fully taken into account for the background index.
- All sensitivities given are the scales for $0\nu\beta\beta$ discovery. To get relative sensitivities for $m_{\beta\beta}$ the square root has to be taken.
- Of the running experiments, Kamland-Zen should have the largest potential. This is impressive if one takes into account that it was not specially built for this physics.
- Germanium experiments can be very competitive despite the fact that the phase space factor is so small. Especially if a positive signal will be claimed, a narrow peak at $Q_{\beta\beta}$ will be more convincing than a broad shoulder.

² A fiducial volume cut will reduce the active mass. Depending on whether the background index is normalized to the total mass or to the fiducial mass, the efficiency ϵ has to go under the square root or not. The meaning of B is not always clearly defined in the literature. Here the normalization to the total mass is assumed.

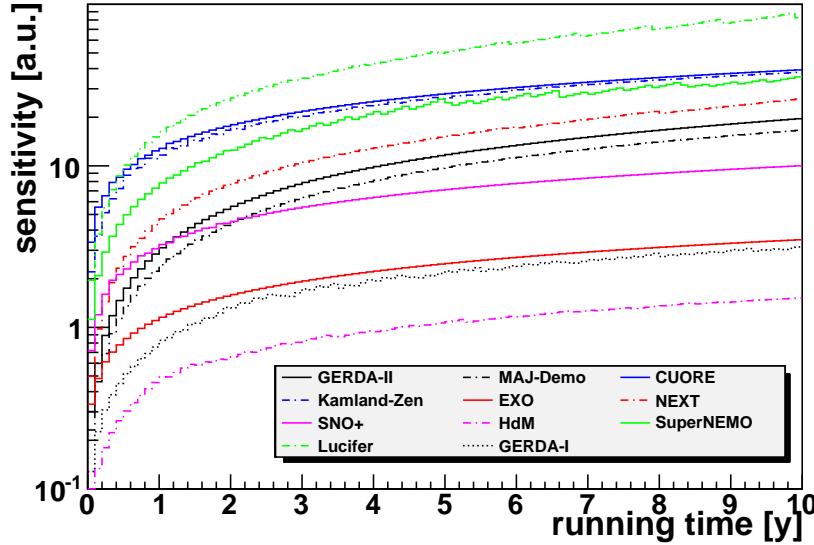


Figure 2. Relative experimental sensitivity for $0\nu\beta\beta$ life time limit versus running time.

- The Lucifer approach with 100 kg is very competitive even in comparison to a ton scale Xe experiment like Kamland-Zen or NEXT.
- Systematic effects like the precision of the energy resolution or the background shape are not taken into account.

In case the neutrino masses are ordered in the inverted mass hierarchy, a lower bound of about 15 meV for $m_{\beta\beta}$ can be calculated using the current parameters from neutrino oscillation experiments. For ^{76}Ge this corresponds to half lives of $5 - 20 \cdot 10^{27}$ years. These values should be compared to the expected sensitivity of GERDA-II or the Majorana Demonstrator of about $1.5 \cdot 10^{26}$ y. This demonstrates that exploring the entire mass band of the inverted hierarchy is a long term enterprise. With the numbers in Tab. 3 and a mass of 1000 kg, the required time for $5 \cdot 10^{27}$ y is 13 years while a Lucifer like experiment would need to run for half the time.

6. Summary

Neutrinoless double beta decay is the best experimentally accessible method to test whether neutrinos are Majorana particles. This decay violates lepton number and is therefore on equal footing to proton decay searches. The motivation for several large efforts in this field is therefore obvious.

For a long time, the Heidelberg-Moscow experiment has dominated the field and its claim of a $0\nu\beta\beta$ signal has not been scrutinized since 2001. In 2011, EXO, Kamland-Zen, CANDLES and GERDA-I started to take data. All but CANDLES are more sensitive than Heidelberg-Moscow and especially Kamland-Zen is expected to answer this question in the next 12 months. EXO has already reported a first time measurement of $T_{1/2}^{2\nu}(^{136}\text{Xe}) = 2.11 \pm 0.04(\text{stat}) \pm 0.21(\text{syst}) \cdot 10^{21}\text{y}$ which is considerably lower than previous limits [15].

Beyond this next step, experiments want to explore the $m_{\beta\beta}$ region for the inverted neutrino mass hierarchy. This will eventually require ton scale experiments. Which of the proposed solutions will be built is open at the moment.

References

- [1] Goeppert-Mayer M 1935 *Phys. Rev.* **48** 512
- [2] Majorana E 1937 *Nuovo Cim.* **14** 171
- [3] Furry W H 1939 *Phys. Rev.* **56** 1184
- [4] Barabash A S 2011 *Phys. Atom. Nucl.* **74** 603 (*Preprint arXiv:1104.2714*)
- [5] Tretyak V I 2011 *conference MEDEX'11, Prague*
- [6] Avignone F T, Elliott S R and Engel J 2008 *Rev. Mod. Phys.* **80** 481 (*Preprint arXiv:0708:1033*)
- [7] Rodejohann W 2011 *Int. J. Mod. Phys. E* **20** 1833 (*Preprint arXiv:1106.1334*)
- [8] Gomez-Cadenas J J *et al.* 2012 *Riv. Nuovo Cim.* **35** 29 (*Preprint arXiv:1109:5515*)
- [9] Suhonen J 2011 *Phys. Lett. B* **701** 490 see also talk at TAUP 2011
- [10] Tretyak V 2011 *conference TAUP 2011, Munich*
- [11] Rukhadze N *et al.* 2011 *Nucl. Phys. A* **852** 197 see also talk at TAUP 2011
- [12] Danevich F 2011 *conference TAUP 2011, Munich, also arXiv:1110.3690*
- [13] Nakamura K and others (Particle Data Group) 2010 *J. Phys. G* **37** 075021
- [14] Barabash A S 2010 *Phys. Rev.* **C81** 035501 (*Preprint arXiv:1003.1005*)
- [15] Ackerman N *et al.* 2011 *Phys. Rev. Lett.* **107** 212501 (*Preprint arXiv:1108.4193*)
- [16] Klapdor-Kleingrothaus H V *et al.* 2004 *Phys. Lett. B* **586** 198
- [17] Menendez J *et al.* 2009 *Nucl. Phys.* **A818** 139 (*Preprint arXiv:0801.3760*)
- [18] Menendez J *et al.* 2009 *Phys. Rev.* **C80** 048501 (*Preprint arXiv:0905.1705*)
- [19] Faessler A *et al.* 2011 *Phys. Rev.* **D83** 113015 (*Preprint arXiv:1103.2504*)
- [20] Simkovic F *et al.* 2009 *Phys. Rev.* **C79** 055501 (*Preprint arXiv:0902:0331*)
- [21] Fang D L *et al.* 2011 *Phys. Rev.* **C83** 034320 (*Preprint arXiv:1101:2149*)
- [22] Suhonen J and Civitarese O 2010 *Nucl. Phys* **A847** 207
- [23] Rodriguez T R and Martinez-Pinedo G 2010 *Phys. Rev. Lett.* **105** 252503 (*Preprint arXiv:1008.5260*)
- [24] Barea J and Iachello F 2009 *Phys. Rev.* **C79** 044301
- [25] Barea J and Iachello F 2011 *Nucl. Phys. B (Proc. Suppl.)* **217** 5
- [26] Rath P K *et al.* 2010 *Phys. Rev.* **C82** 064310 (*Preprint arXiv:1104.3965*)
- [27] Rodin V 2011 *conference TAUP 2011, Munich*
- [28] Escuderos A *et al.* 2010 *J. Phys.* **G37** 125108 (*Preprint arXiv:1001.3519*)
- [29] Gomez-Cadenas J J *et al.* 2011 *JCAP* **2011** 7 (*Preprint arXiv:1010:5112*)
- [30] Guess C J *et al.* 2011 *Phys. Rev.* **C83** 064318 (*Preprint arXiv:1105.0677*)
- [31] Schiffer J P *et al.* 2008 *Phys. Rev. Lett.* **100** 112501 (*Preprint arXiv:0710:0719*)
- [32] Kay B P *et al.* 2009 *Phys. Rev.* **C79** 021301 (*Preprint arXiv:0810.4108*)
- [33] Simkovic F *et al.* 2009 *Phys. Rev.* **C79** 015502 (*Preprint arXiv:0812:0348*)
- [34] Suhonen J and Civitarese O 2008 *Phys. Lett.* **B668** 277
- [35] Hirsch M, Klapdor-Kleingrothaus H V and Kovalenko S G 1998 *Phys. Rev.* **D57** 1947 (*Preprint arXiv: 9707207*)
- [36] Andreotti E *et al.* 2011 *Astropart. Phys.* **34** 822
- [37] Simard L 2011 *conference TAUP 2011, Munich*
- [38] Kozlov A 2011 *conference TAUP 2011, Munich*
- [39] Cattadori C 2011 *conference TAUP 2011, Munich*
- [40] Ogawa I 2011 *conference TAUP 2011, Munich*
- [41] Capilla F M 2011 *conference TAUP 2011, Munich, also arXiv:1106.3630*
- [42] Gorla P 2011 *conference TAUP 2011, Munich, also arXiv:1109.0494*
- [43] Wilkerson J 2011 *conference TAUP 2011, Munich, also arXiv:1111.5578*
- [44] Hartnell J 2011 *conference TAUP 2011, Munich*
- [45] Barabash A 2011 *conference TAUP 2011, Munich, also arXiv:1112.1784*
- [46] Oldorf C 2011 *conference TAUP 2011, Munich*
- [47] Cardani L 2011 *conference TAUP 2011, Munich*
- [48] Ishikawa T *et al.* 2011 *Nucl. Inst. Meth. A* **628** 209
- [49] Fushimi K *et al.* 2010 *J. Phys. Conf. Ser.* **203** 012064
- [50] Yamashita M (XMASS) 2010 Prepared for 6th Patras Workshop on Axions, WIMPs and WISPs, Zurich, Switzerland, 5-9 Jul 2010
- [51] Kornoukhov V 2011 *conference TAUP 2011, Munich*
- [52] Barabash A S 2011 *JINST* **6** P08011 (*Preprint arXiv:1108.2771*)